ANALYSIS FOR COOPERATIVE BEHAVIOR EFFECTIVENESS OF AUTONOMOUS WIDE AREA SEARCH MUNITIONS

THESIS

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Abstract
The purpose of this study is to investigate how a simulation model can accurately represent the performance of the autonomous wide area search munitions, and to find the effectiveness of the cooperative behavior on the autonomous munitions. Though it does not provide a practical solution for the development of the autonomous wide area search munitions, this research will show some meaningful allocations of the munitions tasks that are applicable to the development of the autonomous munitions. For the first phase, this thesis presents how accurately a simplified simulation model can represent a proposed weapon system by comparing the simulation results to the analytical solutions. For the second phase, this research investigates how each mission parameters including cooperative behavior affects the performance of the weapon system.

Subject Terms
Cooperative Engagement, Cooperative Behavior, Autonomous Munitions, Wide Area Search Munitions

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PARK, SANG MORK

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Abstract

The purpose of this study is to investigate how a simulation model can accurately represent the performance of the autonomous wide area search munitions, and to find the effectiveness of the cooperative behavior on the autonomous munitions.

As a prediction tool for measuring the performance of the virtual weapon systems, simulation models are established because there are insufficient analytical tool for the prediction of weapon system performance. Though the simulation models may not accurately represent the actual autonomous weapon system, the result of the simulation may provide expectations of the performance of the autonomous munitions in actual battlefield scenarios. Several assumptions and limitations are necessary in dealing with the problem for the purpose of the simplicity. The assumptions and limitations will be presented in this thesis. Two simulation models were used in this research. One is a highly simplified model for validity investigation, and the other is an AFRL/VACA model which is still in development phase to investigate the effectiveness of cooperative behavior. The simulation result from the simplified simulation model will be compared to the calculated performance predicted from an analytical tool for validity investigation, and it will also dominate the potential effectiveness of cooperative behavior. The result from the AFRL/VACA simulation will also present the effectiveness of cooperative behavior in the virtual weapon system.

This research does not provide a practical solution for the development of the autonomous wide area search munitions. However, this research will show some meaningful allocations of the munitions tasks that are applicable to development of the autonomous munitions.

ANALYSIS FOR COOPERATIVE BEHAVIOR EFFECTIVENESS

OF AUTONOMOUS WIDE AREA SEARCH MUNITIONS

I Introduction

1.1 General

To minimize the loss of life in complicated and intense battlefield circumstances, diverse types of unmanned combat machines are being developed. This trend will continue and necessarily expand for future conflicts. Reduced sizes of combat forces in response to changing national military environments, together with increasing development and procurement cost of weapon systems compels the Air Force to develop new weapon system concepts in order to maintain and enhance the Air Force's ground attack capabilities. There are currently developments in progress for autonomous wide area search and attack munitions that can potentially meet the challenge of maintaining or improving mission effectiveness with a reduced size of Air combat forces. With the development of miniature airframes, target recognition systems and communications systems, we also need to develop cooperative behavior schemes for the munitions. This may be critical to achieve efficient operational performance in diverse battlefield environments, whether it is for search, engagement or a combination of both.

The problem being considered in this study is to find ways to evaluate and improve the effectiveness of cooperative wide area search munitions. There are many uncertain parameters that affect the performance of cooperative munitions such as target

numbers and classification, clutter density, warhead lethality and battlefield terrain. In addition to those factors, variables such as varying target priorities, mission constraints, search patterns of munitions and target mobility will increase the complexity in assessing the effectiveness of cooperative munitions.

This research does not present a practical solution to this intricate problem. This research suggests a tool for evaluating the effectiveness of autonomous search and attack munitions by comparing an analytic solution, a simplified simulation methodology, and a model of decision making for optimal task allocation in several specific scenarios of engagement.

1.2 Background

In response to new challenges associated with the diminishing size of military combat forces, several studies have been commissioned by the US Air Force. The RAND[(1)] study, entitled "New Concepts for Ground Attack", looked at enhancing the Air Force capabilities for ground attack through new technological approaches and operational concepts. This study suggested the development of small, light weight, cost effective autonomous munitions equipped with the ATR[a] seekers, INS/GPS[b] navigation systems and self-operated communication systems. The concept munitions consisted of relatively simple platforms with small but effective payloads and a minimal set of onboard detection devices to sense the battlefield environment and to detect ground targets. The Low Cost Autonomous Attack System(LOCAAS) is a concept demonstration program within the Air Force Research Lab that embodies many lower level ideas presented in the RAND study. The Army is also interested in an autonomous

[a] Autonomous Target Recognition
[b] Inertial Navigation System / Global Positioning System

attack weapon system with similar technological basis and similar operational concepts. The main difference between Air Force and the Army concept is the method of weapon deployment. The Air Force is interested in an air deployment system and the Army is in a ground rocket launch system. However, since the conceptual backgrounds are similar in the operation of the autonomous attack systems, both the Air Force and the Army are investigating methods of cooperative behavior in the systems.

The RAND study discussed the rationale for assessing cooperative behavior of PRAWNs[a]. However, since a fixed decision rule, better known as "swarming algorithm", was used, it did not show differences of effectiveness in the diverse possible decision rules, and the influence of existing non-target and false targets. After weapon swarms are released, they turn on their sensors and search for targets. When the weapons find a target, they home on the target, broadcast target information and commit to the attack phase. Other weapons which are in communication range and meet certain proximity requirements will also converge on the target and commit attacks. The weapons which are out of range will continue to search for another target.

Jacques[(2)] and Gillen[(3)] investigated a different form of a cooperative decision rule, and the influence of several decision variables including false target attack rates in cooperative behavior effectiveness measurement. Gillen introduced a methodology for measuring the effectiveness of cooperative behavior in his thesis. However, the evaluation was limited to numerical simulation due to the absence of an appropriate analytic model. There are insufficient analytical methods for evaluating the effectiveness of cooperative munitions; however a computer simulation can be an effective tool for this purpose. Jacques introduced several analytical tools for evaluating the effectiveness of

[a] Proliferated Autonomous Weapons

cooperative behavior on the autonomous search and attack munitions in the simple battlefield scenarios. The analytical tools provide a means for deciding in a probabilistic sense, whether it is more beneficial to attack a previously engaged target, or continued to search for an undiscovered target.

By comparing simulation results from simplified scenarios with analytical solutions, we can validate computer simulation results representing a practical, yet complex battlefield environment. This validation process enables the simulation tool to be adopted for further measurement of effectiveness under mission scenarios that would be impractical or even impossible to evaluate with the analytical models.

1.3 Objectives

The Objectives of this thesis were to develop effective models for cooperative munition behavior and to examine optimal decision rules for the efficient operation of them in specified battlefield scenarios. To reach the main objective, these four specific sub-objectives are established;

1. Present a methodology to evaluate the expected effectiveness of wide area search munitions;
2. Investigate the validity of simulation tools in a simplified scenario of wide area search munitions;
3. Extend the investigation of multi-munition/multi-target engagement scenarios, and measure the effectiveness of cooperative algorithms to find improved cooperative schemes in specific battlefield environments;
4. Analyze the sensitivity of decision parameters to obtain optimal cooperative scheme in general engagement scenarios;

1.4 Approach

The simulations presented in this study are designed to autonomously search, classify and attack preprogrammed targets with parameterized decision rules. Targets are stationary and randomly located with uniform distribution. The simplified simulation models and analytical solutions measure the expected mission success ratio of autonomous wide area search munitions. The results from the simulation models which use multiple munitions and multiple false targets are, where possible, compared to analytical solutions in order to investigate the validity of the simulation model for measuring the performance of autonomous search and attack munitions.

For the validation process, two forms of cooperative algorithms were used to see if the simulation results match the expected probability of mission success suggested by analytical evaluation. The first one is a non-cooperative case. Each munition attacks targets on the basis of independent target classification information without any communication between munitions. The second one uses cooperative classification and engagement. When a munition classifies what it believes is a valid target, it communicates and calls another munition to confirm the classification of the target. Only when both munitions agree to classify the target as valid, can they perform attacks on the target. If the simulation result can be validated against analytical models for simplified battlefield scenarios, we can then extend the simulation modeling methodology as an efficient tool for measuring the effectiveness of cooperative behavior in generalized battlefield scenarios.

For the second phase of this research, a different computer simulation model was used. Multiple autonomous wide area search munitions search and attack randomly

located valid and false targets in the search area. Though this computer simulation model still does not precisely represent a real world battlefield, it can present more general characteristics of battlefield parameters and show the effectiveness of cooperative behavior.

In order to find optimal values of the parameters to maximize mission effectiveness in diverse virtual battlefield scenarios, a statistical methodology was adopted. Though the parameters that represent a battlefield environment may not be clearly defined in the real world, some of those parameters are given as constant values to set up models of battlefield scenarios. Successive simulations were run to achieve optimal search weight in given scenarios and the sensitivity analysis of decision parameters was accomplished through statistical analysis.

1.5 Scope

This study does not address a general solution of cooperative behavior algorithms for the autonomous wide area search munitions in complicated battlefield environments. This research is intended to investigate the effectiveness of cooperative behavior with communication support. It also presents a methodology to show the optimal values of mission parameters for the highest mission success probability in given engagement scenarios. The simulation model presented in this study does not represent specific autonomous wide area search munitions. Another specified result for the diverse battlefield scenario can be acquired by modifying decision parameters in the simulation. Through the sensitivity analysis of decision parameters, this study may provide a picture of the important parameters that should be considered in diverse battlefield scenarios.

II Autonomous Wide Area Search Munitions

2.1 Characteristics and Operational Concepts

Until recently, attacking ground targets has been a straight forward procedure. When a target surveillance device finds a target, it provides target information to the command and control post. On the basis of this information, the command and control post assigns its' assets to attack the targets and the attacker assaults the target with relatively exact target location and characteristics. However, since the process from target detection to target attack is time consuming, the uncertainty of target information can grow further due to target mobility. The increased uncertainty makes it necessary to set up alternative plans to compensate for it. One of the alternatives that can satisfy mission success requirements in uncertain battlefield environments is to use small, low cost weapons that function cooperatively. Though each of the small weapons is not as lethal as the larger and more expensive ones, cooperative behavior can make up for decreased individual capabilities.

2.1.1 General Characteristic of Proposed Autonomous Munitions

One wide area search munition option is shown in Figure 1. The proposed autonomous munitions fly 200~ 300 m AGL[a] with a speed of 100 m/sec. Each munition has an estimated footprint of 600 m width and 100~ 200 m depth for its ATR[b] search area. It is guided through the INS/GPS[c] and an incorporated communication system for

[a] Above Ground Level
[b] Autonomous Target Recognition
[c] Inertial Navigation System / Global Positioning System

cooperation. It will have one or more warheads to allow engagement of preprogrammed targets.

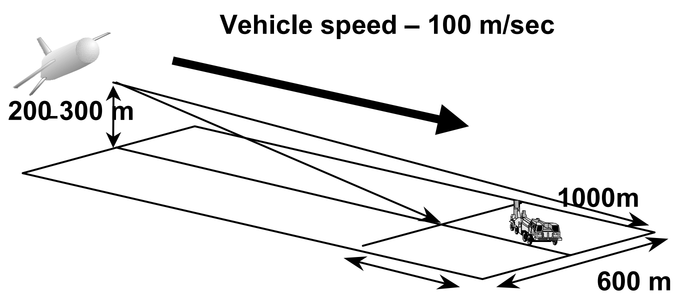

Figure 1 Wide Area Search Munition

2.1.2 Autonomous Target Recognition Algorithm

A methodology to distinguish valid targets from clutter is beyond this study. However, for the purpose of developing a tool to improve the effectiveness of cooperative behavior, we need to consider the performance of the target recognition system. Jacques[(4)] presented a picture of the relationship between the performance of the ATR system and parameters that are dictated by the battlefield environments. He described a confusion matrix of a priori probabilities for correct (2nd incorrect) classification of valid and false targets.

Table 1 Binary Confusion Matrix

Declared Object	Encountered Object: Target	Encountered Object: Non-target
Target	P_{TR}[g]	1- P_{TR}
Non-target	$P_{FTA\|E}$[h]	1- $P_{FTA\|E}$

[g] Probability of Target Report
[h] Probability of False Target Attack given Encountered

The simplest one, shown in Table 1, is the binary confusion matrix discriminating the targets from non-targets. However, the complexity of the battlefield environment may require discrimination between several different valid targets. To implement the complexity of the multiple target types, the confusion matrix needs to be expanded. If we suppose that there are three types of valid targets in the engagement area, and the ATR can distinguish each type of target, the confusion matrix can be expanded to the form of Table 2. Note that an encountered target will be either correctly or incorrectly classified; therefore the probability numbers in each column must sum to one.

Table 2 Multiple Confusion Matrix

	Encountered Object			
Declared Object	Target 1	Target 2	Target 3	Non-target
Target 1	$P_{TR1\|E1}$	$P_{TR1\|E2}$	$P_{TR1\|E3}$	$P_{FTA1\|E}$
Target 2	$P_{TR2\|E1}$	$P_{TR2\|E2}$	$P_{TR2\|E3}$	$P_{FTA2\|E}$
Target 3	$P_{TR3\|E1}$	$P_{TR3\|E2}$	$P_{TR3\|E3}$	$P_{FTA3\|E}$
Non-target	$1-\Sigma P_{TRj\|E1}$	$1-\Sigma P_{TRj\|E2}$	$1-\Sigma P_{TRj\|E3}$	$1-\Sigma P_{FTAj\|E}$

$P_{TRj|Ei}$ represents the probability of reporting target *j* when encountered target *i*. And $P_{FTAj|E}$ represent the probability of reporting target *j* when encountered Non-target.

2.1.3 Implementing Cooperative Behavior

Several specific capabilities are necessary to execute cooperative behavior of autonomous wide search area munitions. Among the required capabilities, the most important three are communication, ATR, and artificial intelligence for on-line decision

making. Since the ATR coverage area of each munition is limited, an RF[i] or IR[j] spectrum based communication system is necessary to share information between individual munitions. If each cooperative vehicle transmits current status through its communication system, vehicles within communication range will be aware of what other munitions are seeing, what they are doing, and what actions are necessary to cooperate for weapon effectiveness improvement.

In a study of ant colony systems, Dorigo[(5)] introduced an *ant algorithm* that applied the behavior of blind animals like ants as a theoretical basis. It was found that ants use pheromone trails to establish the shortest routes from their colony to feeding sources and back. The collective behavior of ants on the basis of the pheromone orienting communication skill can also provide a positive feedback loop that enables other ants to choose mutually beneficial paths. Though the *ant algorithm* does not present an exact solution for implementing cooperative behavior between autonomous munitions, it provides us an indication of behavior that the cooperative search and attack munitions should retain. Three characteristics are proposed to build the *ant algorithm* by using artificial ant colonies as an optimization tool. The artificial agents will have some memory, they will not operate completely blind, and they will live in an environment where time passes in discrete advances.

Other studies of ethology[k] and robotics have been performed to develop organizational decision routines for performing complex tasks under a broad range of conditions. Frelinger[(1)] presented a significant insight of cooperative behavior parameters by introducing a simple set of rules for complex behavior to build a simulation model of

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[i] Radio Frequency
[j] Infra Red
[k] The science of animal behavior

possible autonomous munitions. According to the *ant algorithm,* the ants create chemical trails when food is discovered and carry it to the nest. Since the chemical density gradient indicates the direction of the food source, other ants can acquire more chances to reach the food source by following the chemical trails. He applied this ant foraging behavior rules to a weapon system and suggested an artificial swarm of weapon system that can detect and destroy preprogrammed targets.

2.2 Evaluation of Non-Cooperative Weapon Effectiveness

Although some classic work in the area of optimal target search has been done by Koopman(6),and Washburn(7), an analysis of the multi-target case with false target attacks and cooperative munition behavior has not been available until recently. Jacques(4) presented advances in the evaluation of autonomous munitions mission success probabilities. Jacques used simplified mission parameters in a probabilistic approach. This analytical method presents a good picture for measuring mission effectiveness of autonomous search munitions. Further, it provides a convenient method for evaluation parameter trade-offs and limits of performance for cooperative behavior.

2.2.1 Single Munition and Single Target Scenario

The prediction formula for the mission success probability in a single munition/single target scenario can be expressed as:

$$P_{MS} = P_k \cdot P_{TR} \cdot P_{LOS} \cdot P_E \cdot P_C \qquad (1)$$

where

P_K : The probability of target kill when a target was classified as a valid target

P_{TR} : The probability of correct Target Report when a target is in clear LOS[l]

P_{LOS} : The probability of clear LOS given target is in the FOR[m]

P_E : The probability of encountering a target when the target is in the search area

P_C : The probability of the target being contained in the assigned search area

With the exception of P_E, the probabilities are expressed as either single numerical values, or as is the case for P_{TR}, a table of values referred to as a confusion matrix as discussed earlier. P_E stands for the probability that a munition will not engage any false targets and continue search until it finds a valid target. It can be expressed as a function of the area to be searched (A_S) and a False Target Attack Rate α .

$$P_E(A_S) = \frac{1 - e^{-\alpha \cdot A_S}}{\alpha \cdot A_S} \qquad (2)$$

Formula (2) is useful for the analysis of single munition/single target scenarios, but it must be modified for the general multi-munition/multi-target scenarios.

The False Target Attack Rate (α) means the expected number of false target attacks per unit area for a seeker operated in a non-commit (search only) mode.

$$\alpha = \eta \cdot P_{FTA|E} \qquad (3)$$

where η represents the expected density of the false targets that can be confused as valid targets, and $P_{FTA|E}$ is the probability of attacking when a false target is encountered. Consider an autonomous munition looking for a valid target among the false targets. We shall assume that a valid target and several false targets are uniformly distributed in search area A_S. False targets are considered to be any objects that can potentially cause

[l] Line of Sight
[m] Field of Regard

the autonomous target recognition algorithm to be fooled. Since we are considering single shot munitions, the probability that the munitions will successfully engage a valid target in the incremental ΔA is conditioned on probability of not engaging a false target prior to arriving at ΔA. The density function of encountering a valid target in ΔA can be expressed as:

$$\Delta P_E = P_{\overline{FTA}}(A).\frac{\Delta A}{A_S} \tag{4}$$

where $P_{\overline{FTA}}(A)$ represents the probability of no false target engagement until the munition reaches the next incremental search area ΔA. For an unknown number of uniformly distributed false targets, the expected number of false target engagements will follow the Poisson distribution rule with respect to the mean number of false targets in the area searched. The probability of exactly *j* false target declarations while searching the area A has a Poisson distribution with parameter $\lambda = \alpha \cdot A$:

$$P_{j,A} = \frac{(\alpha \cdot A)^j e^{-\alpha \cdot A}}{j!} \tag{5}$$

where *j* represents the number of false target engagements. The probability of no false target engagement in search area A can be described as:

$$P_{\overline{FTA}}(A) = P_{0,A} = e^{-\alpha \cdot A} \tag{6}$$

Based on the equations from (3) through (5), we can formulate the expected probability of encountering a valid target without executing a false target attack in search area A_S as:

$$P_E(A_S) = \int_0^{A_S} \frac{e^{-\alpha \cdot A}}{A_S} dA = \frac{1 - e^{-\alpha A_S}}{\alpha \cdot A_S} \tag{7}$$

yielding the same result as equation (2).

2.2.2 Multi Munition and Multi Target Scenario

Expanding on the single-munition/single-target case analysis, we can improve the analytical tool to explain multi-munition/multi-target scenarios. Jacques showed several additional parameters that need to be considered for the analysis of complex battlefield scenarios. For the first phase, the autonomous search munitions should determine how to allocate each munition's search area for improving the probability of valid target classification.

The simplest and easiest way is to divide the total search area into several sub-areas based on the number of munitions, and make each munition execute an independent search and engagement within its assigned sub-area. This scheme may result in increased mission success because the reduced search area assigned to each munition means higher possibilities of encounter for targets in those sub areas. However, the mission success probability will still be limited by other operational parameters such as P_K and P_{TR} of a single munition since this method assumes no overlap of the search area and single munition engagement only.

Another way to compensate for reduced capability of each munition, and to increase mission success probability, is to have the munitions share the whole search area. We can expect better results of engagement by overlapping the search areas and provoking multiple target attacks. Extending the mission success prediction formula from the single-munition/single-target case to the multi-munition/multi-target case produces rapid complications as we consider increased numbers of operational parameters such as the search path and degree of correlation between munition/target encounters. We will assume that target classification and engagement behavior of each

munition are independent for this simple analysis, even though the assumption of perfectly uncorrelated behavior of homogenous munitions is not strictly valid.

When we consider a multi-munition/single-target scenario, the probability of killing the target in search area A_S with N multiple munitions is expressed as:

$$P_{MS}^{[N]}(A_S) = \sum_{n=1}^{N} P_K^{[n]} \cdot P_E^{[n]}(A_S) \qquad (8)$$

To derive $P_E^{[n]}(A_S)$, the probability of n munitions encountering the valid target, we shall consider additional factors based on the direction of the munition's target search. The two patterns considered here are defined as the same search path and the opposite search path in this research. The munitions move in the same direction and share the same footprints when the same search path is chosen. The munitions move in the opposite direction over the same area when the opposite search path is adopted.

Consider a case of two identical munitions searching for a single uniformly distributed valid target and a Poisson field of false targets in search area A_S. When the munitions follow the same search path, the probability that one of the two munitions will encounter the valid target is

$$P_E^{[1]}(A) = 2e^{-\alpha \cdot A}(1 - e^{-\alpha \cdot A}) \qquad (9)$$

and the probability of both munitions encountering the valid target is

$$P_E^{[2]}(A) = e^{-2\alpha \cdot A} \qquad (10)$$

The probability of kill when the two munitions encountered the valid target is

$$(1 - (1 - P_K \cdot P_{TR})^2) \qquad (11)$$

The equation for the probability of the valid target kills is addressed as:

$$P_{MS_S}^{[2]}(A_S) = P_C \int_0^{A_S} (P_K \cdot P_{TR} \cdot 2e^{-\alpha \cdot A}(1-e^{-\alpha \cdot A}) + (1-(1-P_K \cdot P_{TR})^2)e^{-2\alpha \cdot A})\frac{dA}{A_S}$$

$$= P_C \cdot P_K \cdot P_{TR}(\frac{2}{\alpha \cdot A_S}(1-e^{-\alpha \cdot A_S}) - \frac{P_K P_{TR}(1-e^{-2\alpha \cdot A_S})}{2\alpha \cdot A_S}) \qquad (12)$$

For the case where the opposite path is selected, the probability of encountering the valid target for the forward search munition is

$$P_{Ef}(A) = e^{-\alpha \cdot A} \qquad (13)$$

The probability of encountering the valid target for the opposite search munition is

$$P_{Er}(A) = e^{-\alpha(A_S - A)} \qquad (14)$$

and the probability of both munitions encountering the valid target is

$$P_E^2(A) = e^{-\alpha \cdot A} \cdot e^{-\alpha(A_S - A)} = e^{-\alpha \cdot A_S} \qquad (15)$$

With the equations from (13) through (15), we can formulate the probability of mission success for two munitions searching for one valid target through opposite paths as:

$$P_{MS_O}^{[2]}(A_S) = P_C \int_0^{A_S} P_K \cdot P_{TR}(e^{-\alpha \cdot A} + e^{-\alpha \cdot (A_S - A)}) - 2e^{-\alpha \cdot A_S} + (2 - P_K \cdot P_{TR})e^{-2\alpha \cdot A_S})\frac{dA}{A_S}$$

$$= P_C \cdot P_K \cdot P_{TR}(\frac{2}{\alpha \cdot A_S}(1-e^{-\alpha \cdot A_S}) - P_K P_{TR} e^{-\alpha \cdot A_S}) \qquad (16)$$

When the same mission parameters are adopted, we can find that the mission success probability of the opposite search path is higher than that of the same search path. The difference between the two mission success probabilities is due to the different probabilities of encountering the valid target. Equations (10) and (15) show the expected probabilities of encountering the valid target when two munitions search the valid target

following same search path and opposite search path. Figure 2 shows the expected mission probabilities of each search path when other mission parameters are the same.

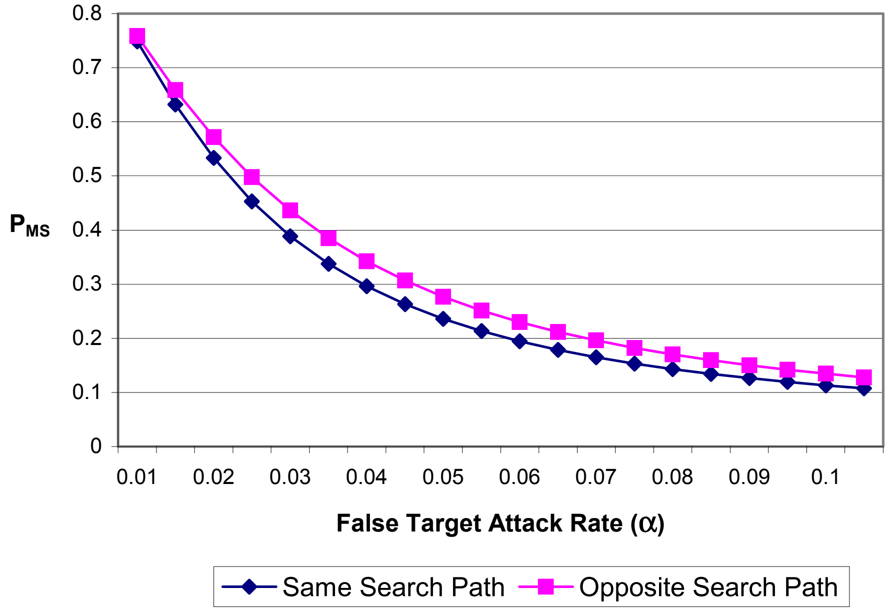


Figure 2 Mission Success Probabilities

2.3 Implications for Cooperative Behavior

According to Jacques, the two most basic cooperative behaviors for the wide area search munition problem are cooperative classification and cooperative engagement. Cooperative engagement is defined as a case where multiple munitions execute attacks on a target classified by a single munition. Cooperative classification is defined as a case that requires multiple looks from one or more munitions in order to acquire the predetermined certainty of correct target classification.

For a correctly identified target, cooperative engagement has definite benefits in enhancing the mission success by the increase of $P_K^{[N]}$ due to multiple attacks being executed. The probability of kill with given multiple attacks is expressed as:

$$P_K^{[N]} = 1 - (1 - P_K)^N \qquad (17)$$

However, for an incorrectly identified target, cooperative engagement results in significant losses from wasting valuable resources without any gains. To reduce the probability of wasting valuable munitions, we can set up a decision rule that may improve the probability of mission success through comparative estimation between the mission success probability of continued search and that of immediate engagements.

When a munition encounters a valid target, the munition may classify it as either a valid one or a false one. Using a selective estimation decision rule, if a munition misjudges a valid target as a false one, it will bypass the target without attacking and remain in the search mode. But when it correctly recognizes a valid target, the munition can choose to attack the target, or to continue to search for additional or higher priority targets. The decision rule for the choice between continued search and immediate attack is dependent on the comparison of the two mission success probabilities. While adopting the comparative decision rule proposed here can improve the mission success possibility by decreasing useless losses of resources, it can also drop the mission success possibility by increasing the probability of bypassing valid targets without attacking them.

When we consider a case of an autonomous munition searching for uniformly distributed targets among uniformly distributed clutter targets, one of three possible outcomes will occur; valid target attack, false target attack and out of gas without any attack.

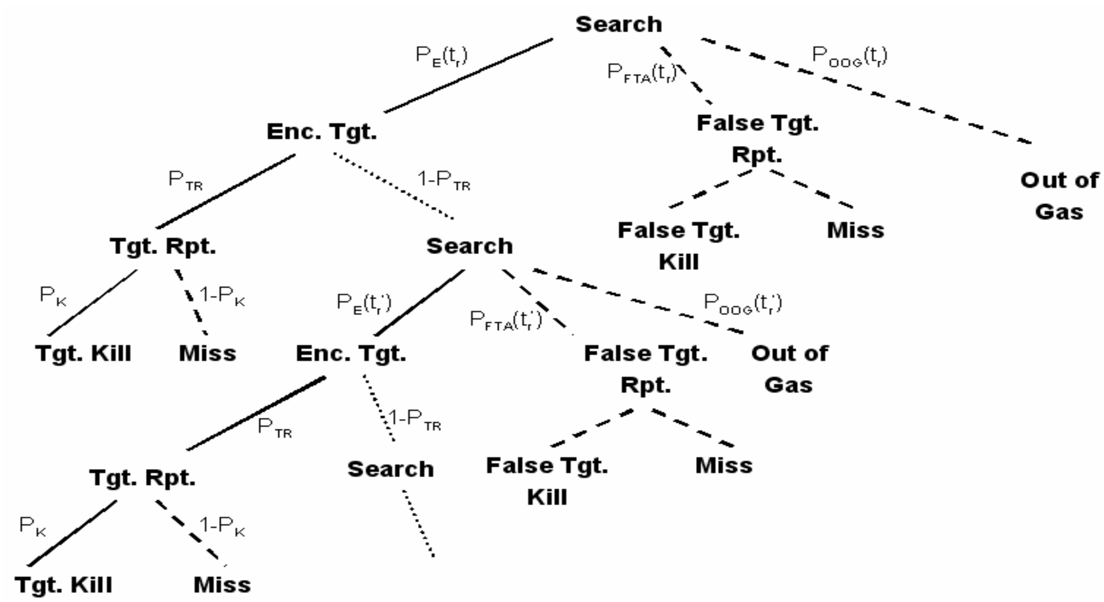


Figure 3 Possible Search Outcome Tree

Figure 3 presents possible search outcomes for a single munition searching for multiple valid targets. The expected probabilities of each case during the remaining life of the munition, t_r, can be stated as:

$$P_{RT}(t_r) = \frac{P_{TR} \cdot \eta_T}{\alpha + P_{TR} \cdot \eta_T}(1 - e^{-(\alpha + P_{TR} \cdot \eta_T) V \cdot t_r \cdot W}) \qquad (18)$$

$$P_{FTA}(t_r) = \frac{\alpha}{\alpha + P_{TR} \cdot \eta_T}(1 - e^{-(\alpha + P_{TR} \cdot \eta_T) V \cdot t_r \cdot W}) \qquad (19)$$

$$P_{OOG}(t_r) = e^{-(\alpha + P_{TR} \cdot \eta_T) V \cdot t_r \cdot W} \qquad (20)$$

Equation (18) stands for the probability of target report, Equation (19) stands for the probability of false target attack, and Equation (20) stands for the probability of running out of gas without any target attack. The probability of killing a valid target for a munition that is in the search mode during the remaining time of t_r can be expressed as:

$$P_{CS}(t_r) = P_K \cdot P_{RT}(t_r) \qquad (21)$$

where $V \cdot t_r \cdot W$ represents the area that the munition can cover in the remaining life of t_r with velocity V and search width W.

Consider a case of cooperative engagement between two autonomous munitions. If a munition encounters a valid target and declares it to be a valid, the other munition will choose to engage or to continue to search. The decision tree that shows options for the second munition to choose is presented in Figure 4.

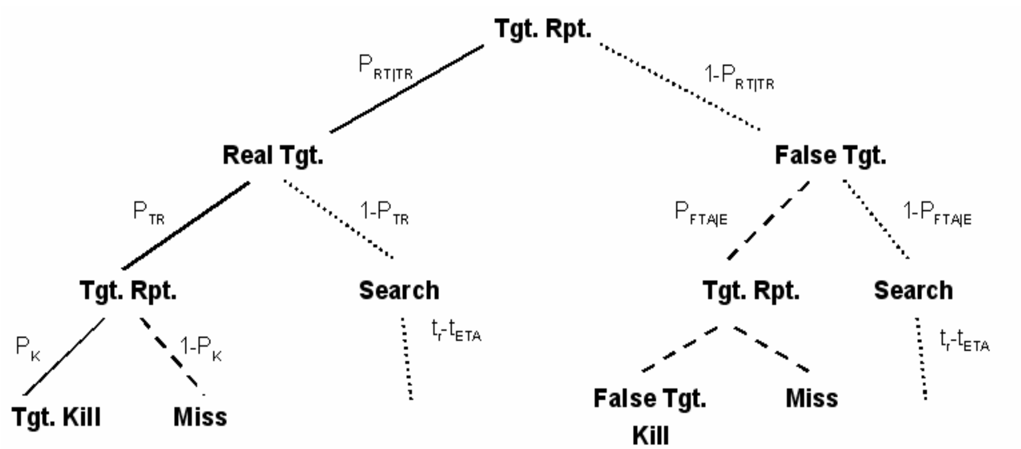


Figure 4 Possible Engagement Outcome Tree

When a munition declares a target to be valid, the probability of it being a real target is

$$P_{RT|TR} = \frac{P_{TR} \cdot \eta_T}{P_{TR} \cdot \eta_T + P_{FTA|E} \cdot \eta} \qquad (22)$$

where η_T represents the valid target density and η represents the false target density in the search area A_S. With the decision tree and equations of (21) and (22), we can formulate the expected gain of mission success probability by the second munition engaging the target declared to be valid.

$$P_{SA}(t_r) = P_K \cdot P_{TR} \cdot P_{RT|TR} \qquad (23)$$

Equations (21) and (23) represent the mission success probability of continued search and immediate engagement respectively, but do not reflect the multiple attack scenarios. If the first munition attacks the target that it classifies as valid before the second munition decides to engage or not, the probability of target killed from the first attack should be considered in the second munitions decision by changing the density of real targets (the search option), or by multiplying $(1-P_K)$ in front of the first term in equation (23) (the engagement option).

For the general multi-munition/multi-target cases, we shall extend the scope of equations (21) and (23). When a munition encounters a valid target, it will broadcast its target information and compare the two mission success probabilities of the continued search and the immediate attacks derived from the modification of equations (21) and (23). It will then execute the option having the highest probability of mission success. With the target information provided by the first munition, other munitions will select cooperative search or engagement based on the value of the mission success probability.

Cooperative classification may also help improve mission effectiveness since an added benefit of cooperative classification is a reduction in the chance of false target attacks. However, it may also increase the chance of missing valid targets. The simplest implementation of cooperative classification would be to carry out two subsequent looks before declaring it as a valid target. This simple multi-look strategy for target classification will decrease the effective false target attack rate by reducing the probability of false target attack given false target encounter to

$$\alpha^* = (P_{FTA|E})^N \cdot \eta \qquad (24)$$

This simple multi-look method has a detrimental effect that makes the probability of correct target report decrease to the products of “single-look” values.

With the cooperative target classification, the munition can have several options for its engagement behavior. Jacques presented an analysis of cooperative classification and engagement behavior with a simple scenario of double munition and single target. If the two munitions classify and attack a target with cooperation, the mission success probability can be bounded by the probability calculation having no concern with the search pattern. If we assume zero delay for the cooperative classification, the mission success probability of the two identical munitions searching for the same target can be expressed as:

$$P_{MS} = (1-(1-P_K)^2)\cdot P_{TR}^2 \cdot (\frac{1-e^{\alpha^*\cdot A_S}}{\alpha^*\cdot A_S}) \qquad (25)$$

where $\alpha^* = (P_{FTA|E})^2 \cdot \eta$.

III Modeling Wide Area Search Munition

3.1 Experiment Designs

Since the real world battlefield involves many complexities and easily changing parameters, it is difficult to develop analytical tools that can predict the result of real world battlefield operations. A computer simulation model can be a general solution for this problem. A computer simulation can provide a representation of a proposed system that follows pre-defined operational rules with enough flexibility to study the effect of different kinds of mission parameters. For the purpose of this research, two MATLAB based simulations were used.

For the first phase, which investigates the usefulness of simulation as a method for predicting the effectiveness of cooperative behavior, a simplified simulation model was developed. As a consequence of the simplification process, the first simulation model does not represent real world battlefield operations. However this study may prove the usefulness of simulation modeling as a mission success prediction method for cooperative munitions. To distinguish this model from the modified AFRL/VACA[n] simulation model, it is defined as the Validity Investigation Model in this research.

The second phase investigates the influences of several mission parameters and evaluates various optimal engagement rules in given battlefield scenarios. For this, a simulation model which still is in the development phase by the AFRL/VACA was used. Though this simulation model sought to represent actual battlefield scenarios, it still has limitations that restrict practical application. Its limitations and modifications of original

[n] Air Force Research Laboratory / Air Vehicles Directorate of the AFRL

simulation codes will be discussed in the following section. The modified AFRL/VACA simulation model is defined as the Cooperative Behavior Investigation Model in this research.

A statistical design of the experiment was developed in order to determine which data runs, and how many would be needed. Due to the extensive time required for some of the simulations, the number of runs had to be limited and the analysis of each experiment was restricted to several specific battlefield scenarios.

3.2 Validity Investigation Model

Though it could not accurately describe the real world battlefield, a simple simulation model was developed to investigate if it could predict the capability of autonomous wide area search munitions accurately and how effective the cooperative behavior is in given engagement rules.

The analytical tools used for measuring the mission success probability of autonomous wide area search munitions were presented by Jacques[2] in his work commented on in the previous chapter. The simulation model for validity investigation presented in this section was developed to represent simple battlefield scenarios. Mission parameters varied were: 1) Two types of search patterns, 2) Varying false target density, 3) Probability of kill, 4) Probability of false target engagement given false target encountered and 5) Probability of correct target report. Detailed discussion of the variables and the simulation architecture will be presented in the following sections.

3.2.1 Design Concept

The functional concept of the autonomous search munitions for validity investigation is based on the general characteristics of the munitions commented on in the previous chapter. The targets are non-moving and uniformly distributed. The munitions, having an ATR seeker, fly over 100 km^2 of search area at the speed of 100 m/sec.

The parameters considered in the simulations were the search pattern, the probability of target report, the false target attack rate, the cooperative scheme and the probability of kill given attacked. Each parameter has its range of variation, but the simulation model did not consider the whole range due to the limits of experimental resources. Several representative values were selected to illustrate the influence of parameters in specific battlefield scenarios, and the parameters that seemed to be ambiguous in real world engagements were assumed to be known and were assigned discrete values.

Only two kinds of targets, representing valid and false targets, were considered for the purpose of simplicity in the simulation model. A small number of valid target scenarios were considered, and the number of false targets varied based on the false target attack rate and the munition's probability of false target attack given encounter.

3.2.2 Design of Munitions

The simulation model employed two munitions for the first stage of the experiment. They follow two separate search patterns based on the initial position of each munition. When the identical search pattern is adopted, each munition starts from the same initial position and moves through the same trail and sharing the same footprints.

When the opposite search pattern is adopted, each munition starts from the opposite edge of the search area and moves through the opposite trail. The search patterns and search area are depicted in Figure 5.

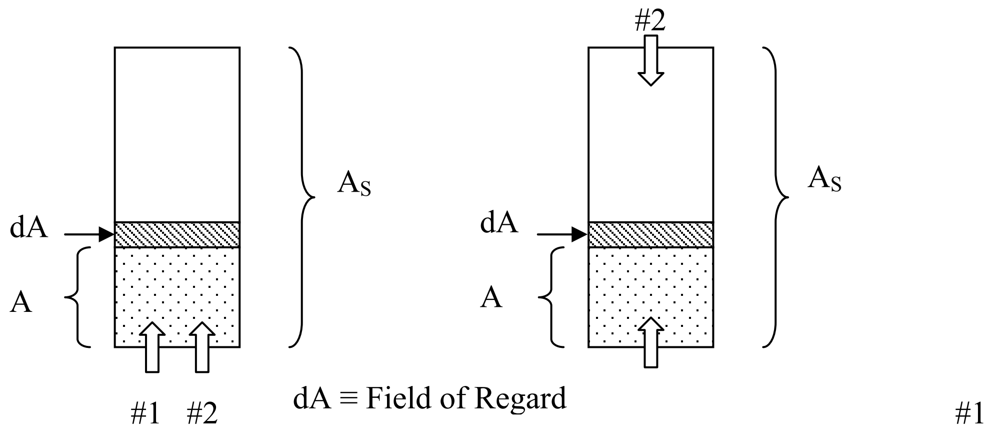


Figure 5 Identical Search Pattern vs Opposite Search Pattern

For the target detection capability, each munition is loaded with a target recognition system that is designed to have a specified *a priori* valid and false target recognition capability. The FOV[o] of the ATR sensor is designed to have a 100 m length and a 1 km width. When an object is included in the discrete search area, the munition classifies it as either a valid target or a false one, and makes use of the target information as an engagement decision parameter.

The munitions can behave either independently or cooperatively in order to study how much the mission success probability can be improved when the munitions use cooperative behavior. In the non-cooperative behavior scenarios, the munitions make attack decisions based on the independently obtained target classification information. When a munition classifies an object as a valid target, it will compare the expected probability of valid target kill resulting from immediate attack to the expected probability

[o] Field of View

of valid target kill from continued search. For equal priority targets, immediate attack will always outweigh continued search. The munitions will follow a different rule of engagement when cooperative behavior scenarios are chosen. When a munition classifies a target as a valid one, it will broadcast the target classification information and call another munition to look at the target. If the second munition confirms the classification, both munitions execute simultaneous attacks.

The munitions created for this simulation model are assumed to have single attack capacity. They have a single warhead which destroys the munition upon detonation. The lethality varies with characteristics of targets and munitions, and it also affects the capability of weapons and optimal decision rules for maximizing effectiveness in given battlefield scenarios. For developing real world weapon systems, it is necessary to trade off between the lethality of a munition and other factors such as the munition size, viability, mission durations, and manufacturing cost since the amount of explosives may limit the amount of fuel, flying speed and loading of other equipments. Only two cases of P_K[p] were considered in this experiment.

3.2.3 Design of Theater

The designed area of engagement is 100 km^2. To prevent the munitions from going out of the search area and to eliminate the turning time of munitions, the theater consists of 100 km in the direction of a munition's movement, and 1 km of width(the same as the width of FOV). Refer to Figure 5. Though the terrain of the theater will significantly affect the distribution of targets and target search plans, it is not considered as a mission parameter in this simplified simulation model.

[p] Probability of Kill given correct target report

The targets are stationary and uniformly distributed within the search area. Though there are different kinds of targets that can be sorted out from the target characteristics in the real world theater, they can be discriminated as valid targets and non-targets for the purpose of simplicity. Only two types of targets, valid targets and non-targets, are considered for exploring the ATR performance of autonomous munitions and the effectiveness of cooperative behavior in this simulation model. One and two valid targets are considered, and the number of false targets varies according to the specified false target attack rate.

3.2.4 Simulation Model

To make a simulation model represent a real world system accurately, we should understand the object of the system and gather precise information on the system. Then we need to design the simulation model to capture the important characteristics of the system as they relate to the objective under investigation. Many systems are too complicated to describe all the capacity and functions, and often the experimental resources are limited. For these reasons, it is necessary to simplify the simulation model when we try to do an experiment for a specific purpose. The design of autonomous munitions and operational environments, described in the previous sections, are not enough to illustrate the operation of the autonomous search munition system. However, we can establish a simulation model to gather some useful information within the scope of operational designs as presented in the previous sections.

A simulation can be described as a process that follows the ordered sequence of events, and the munitions and targets are entities of this simulation model. The flow of the simulation sequence that is shown in Figure 6 is based on discrete time events. The

events and decision logics are coded with MATLAB to represent the function of autonomous munitions and rules of engagement.

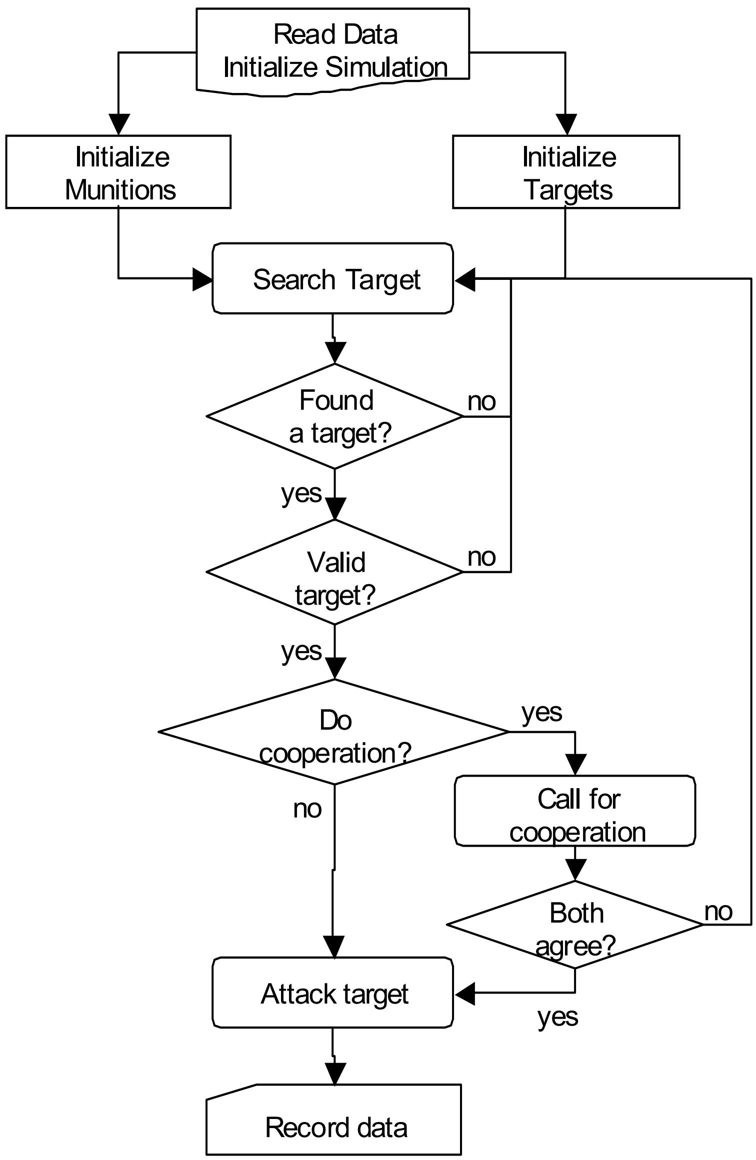


Figure 6 Flow Chart of Validity Investigation Model

The environmental parameters and functional capacities of the autonomous munitions are given to initialize the simulation. A search begins when the munitions start

to move, using one second time increment. When a munition encounters an object, it classifies the object as either a valid target or false target by random draw comparison with a binary confusion matrix. If the munition classifies the target as a valid one, it will decide which cooperative behavior option is adopted. When no-cooperation is assumed, the munition will execute an attack on the basis of its own information. However, when cooperation is assumed, the munition calls for another munition to look at the object for cooperative classification. Only when both of the munitions agree it is a valid target will the munitions execute their attacks.

The number of valid/false target attacks and the number of valid/false target kills are recorded as the mission result. One hundred repetitions of each run are executed in each scenario for statistical analysis of the data. Though the statistical analysis does not guarantee prediction of real world mission results, it will provide us reasonable insights about the function of autonomous munitions and the effectiveness of the cooperative behavior scheme.

3.3 Cooperative Behavior Investigation Model

The original simulation model for the second phase of this research was developed by AFRL/VACA and is still in the developmental phase for the study of cooperative behavior in autonomous wide area search munitions. Though the simulation model includes more mission parameters and decision making logic than the simulation model discussed in the previous sections, it still has limitations and simplifications of the mission success factors. Dunkel[5] investigated the effectiveness of cooperative behavior in the autonomous munitions through modification of the original VACA simulation. The simulation model for the second phase of this research is the extension of the

simulation model modified by Dunkel. The limitations and functional modifications of the simulation will be discussed in the following sections.

3.3.1 Basic Simulation Model

The conceptual design of the simulation model is founded on the general characteristics of autonomous wide area search munitions, and the typical operation of this simulation is not significantly different from the simulation model of the validity investigation discussed in section 3.2. The munitions start from the pre-determined positions and follow a serpentine search track (lawn mower sweep) to detect targets. When they encounter targets, they classify and attack targets individually or cooperatively, based on programmed decision rules.

The VACA simulation model includes additional decision rules and operational functions which are not considered in the previous simulation model. As for the functional design realizations, the simulation model can increase the number of munitions to eight, and the number of targets to thirty. The simulation allows five target types (including non-targets) in order to allow for investigating the effects of varying target priorities on cooperative behavior. Further, the ATR can vary the target recognition probability as a function of the different viewing angle to the targets.

Several decision rules are incorporated in the simulation. When a vehicle encounters an object and classifies it as a valid target, it calculates task benefits and determines a task that allows for maximum benefits across all munitions. The possible options when a munition classifies a target as a valid one are continuing search, re-classification, attacking, and battle damage assessment. The task allocation process that assigns the optimal tasks to the munitions currently uses a capacitated transshipment

problem as described in Schumachers[8] work. A time-phased network optimization model was established to solve the transshipment problem. The model determines optimal task allocations simultaneously and independently at discrete time points considering each munitions conditions and acquired target information. The resulting network optimization problem is re-solved for each discrete target state change, or after preset time intervals.

Dunkel[9] proposed a mathematical method for deriving task benefits when the munition allocates a task. The expected benefits of mission success probability were presented in section 2.2. Equations (12) and (16) show the expected probability of mission success when the munition continues the search. Equation (23) represents the mission success probability when the munition executes an attack on a target that has been previously declared valid. Though the mission success probabilities are derived analytically and may provide a candidate behavior scheme for the optimal task allocation, they do not guarantee the maximum benefits of the multi-munition system. This is because the benefits of operations can be changed easily by the battlefield environments, operational and strategic purposes. The alteration of benefit calculation and operational limitations will affect the munition's task allocation process. A weighting factor, ξ, was applied to determine the best task weighting for a given scenario. The benefit of continuing search targets can be expressed as:

$$\textit{Search Benefit} = \xi \cdot P_{SS} \qquad (26)$$

where P_{SS} represents the mission success probability of continue search. The weighting factor(ξ) varied from 0.1 to 0.9 with 0.1 increment to find maximum mission success probability.

When we calculate the benefit of the target attacks, more factors such as the probability of targets being alive, estimated time of arrival for a munition's second engagement and different benefits of target kills based on the target types, should be considered. Each munition is assumed to be loaded with a communication system for delivering and receiving the target information and the status of other munitions. It may not be practical to know how many attacks are executed on a given target in the battlefield since the probability of identifying a target to be the same one with multiple looks may be difficult, especially when mobile targets are considered. However, for the stationary target scenarios considered here, the number of attacks executed on a target can be communicated to other munitions. The probability of a target being alive after n previous attacks are performed can be expressed as:

$$P_{alive|n-attacks} = (1 - P_K)^n \tag{27}$$

The expected time of arrival can be a significant factor for calculating the expected benefit of attacking the target. When a munition is called on for multiple classifications or multiple attacks, the munition should have enough life remaining to reach the target. Further, one needs to consider the loss of search time as a result of transit time to the target. The attack benefit considering the probability of the target being alive and expected time of arrival can be expressed as:

$$\begin{aligned} P_{SA} &= (1 - P_K)^n \cdot P_K \cdot P_{TR} \cdot P_{RT|TR} + P_{CS}(t_r - t_{ETA}) \cdot (1 - P_{TR}) \cdot P_{RT|TR} \\ &\quad + P_{CS}(t_r - t_{ETA}) \cdot (1 - P_{FTA|FT}) \cdot (1 - P_{RT|TR}) \end{aligned} \tag{28}$$

$$\textit{Attack Benefit} = (1 - \xi) \cdot P_{SA} \tag{29}$$

The attack benefit can be changed by the target priority that is determined based on the types of valid targets. In the real world battlefield there might be different kinds of

targets that have different operational worth. The target priority can be determined by the mission planners. If a munition can identify the type of valid targets, it can grade the value of the target based on the target priority. If the munition identifies an object as a non-target, the attack benefit for attacking it will be scored as zero. Though the attack priority is an important parameter for the optimal decision rule, all valid targets were assumed to have the same priority in this research effort.

3.3.2 Simulation Model Modification

No significant modifications were made for the second phase of the research. The modified portions of the simulation are the forms of input parameters, output data, cooperative behavior activation features and the range of input parameters. Though the modification might not change the actual works of simulation, the modification is necessary to analyze the influence of each parameter alteration on the performance of cooperative behavior.

3.3.3 Simulation Parameter Allocation

The simulations were run in a Monte Carlo fashion. The mission parameters, such as the probability of target report and the probability of target kill given correct target report, were given constant values within certain ranges. At the moment of making a decision, the value of mission parameters are compared with the random numbers derived from specific seeds of the random number generator. Because of the limitation of resources, a limited set of discrete numbers was chosen as the variation of the mission parameters. Although the mission parameters in a real world battlefield will not be given in the form of discrete numbers, it seems meaningful to look into the effect of each

parameter by exploiting the representative value of the mission parameters. The selected values of the mission parameters will be given in the following chapter.

IV Simulation Result and Analysis

4.1 General Consideration

The output data derived from the simulations are provided in the form of quantitative values for each battlefield scenario. The input variables representing the battlefield scenarios were discussed in the previous chapter. These parameters can be sorted into two categories.

- Munitions Parameters:
  - ATR metrics: P_{TR}, $P_{FTA|E}$
  - Warhead lethality: P_K
  - Number of munitions
  - Search pattern: Same search path / Opposite search path
- Battlefield Characteristics
  - Target density
  - False target density

From the operator's point of view, parameters such as false target density(η) and valid target density(η_T) are environmental factors that the operator cannot control on the battlefield. Other parameters such as P_K, P_{TR} and $P_{FTA|E}$ are system parameters that are difficult to change once the munition system is fielded. The other parameters such as number of munitions and search patterns are the operational factors that the mission planner can choose for the maximum mission success probability with minimum consumption of mission resources. It may not be useful to discriminate the operational factors from the environmental factors and system parameters because this research deals

with the development and design of the autonomous munitions. However, to make the analysis simple, the analysis of output data will focus on the decision factors while the operational factors are varied.

4.2 Validity Investigation Model

The first step of this research is to investigate the usefulness of a simulation model for the evaluation of the autonomous wide area search munitions capabilities. The simulation model representing the simple battlefield scenarios provided a predicted value for mission success probability. For the purpose of validity investigation, the results of the simulation were compared to the calculated values of mission success predictions which were derived by the analytic equations presented in Chapter 2.

The second step of this research analyzes the effectiveness of the cooperative behavior in the munitions. The simulation models were manipulated for the munitions to perform cooperation based on the decision rules depicted in the previous chapter. The parameters describing the battlefield scenarios were assumed to be the same as those of the first step simulation models.

Twenty-four scenarios were selected for the representation of the battlefield situations. Simulation runs were done for each set of mission parameters for the purpose of both the validity investigation and the cooperative behavior analysis. To make the simulation model simple, the mission parameters which were selected as representatives of battlefield scenarios are assumed as constant values and the value of each mission parameter were chosen to match previous research by Gillen[3] and Dunkel[9]. The ranges for the selected mission parameters are in Table 3.

Table 3 Simulation Parameters Allocation (Validity Investigation Model)

Parameters	Conditions	Range
P_{TR}	Represent the ATR capability	0.8, 0.9
FTAR	False Target Attack Rate	0.005, 0.01, 0.05
P_K	Represent the lethality of warhead	0.5, 0.8
Search Pattern	Represent the path of trail	Same/Opposite path

The analysis of the validation process will be provided in section 4.2.1, and the analysis of the cooperative behavior will be given in section 4.2.2.

4.2.1 Validity Investigation

The simulation model for the validity investigation was set up using a single target scenario with two munitions. The results derived from the simulation are the expectations that the valid target is destroyed in the virtual battlefield scenarios.

The analytical solutions came from the calculation of equations (12) and (16). Equation (12) presents the probability of target kill when both of the munitions follow the same search path. Equation (16) presents the probability of target kill when the munitions search along opposite paths. The analytical solution to the expected probability of target kill appears in the *Analytical Calculation* column, and the results of simulation are in the *Simulation Result* column in Table 4.

As discussed in Chapter 3, there are many mission parameters that can affect the performance of the autonomous munitions. However, time limits for this thesis research made it difficult to look into the influences of all the mission parameters. For the purpose of simplicity, only four mission parameters variations are considered. The other parameters that were not presented as parameters in Table 4 are considered as constant

values. The simulation results are presented with statistical analysis. Though it is pretty high considering limited resources, the simulation was run for totally 3,000 repetitions that consist of 30 runs executing 100 repetitions in each run, yielding high statistical confidence for the given model.

Table 4 Simulation Result vs Analytical Calculation

Parameters				Simulation Result		Analytical Calculation	Difference
Search PTN	P_{TR}	FTAR	P_K	Mean	Std Dev		
Same Path	0.8	0.005	0.5	0.516	0.061	0.528	2.3%
			0.8	0.723	0.045	0.748	3.4%
		0.01	0.5	0.419	0.050	0.437	4.0%
			0.8	0.613	0.043	0.632	3.0%
		0.05	0.5	0.143	0.032	0.143	-0.1%
			0.8	0.204	0.027	0.213	4.4%
	0.9	0.005	0.5	0.572	0.064	0.580	1.4%
			0.8	0.793	0.048	0.806	1.6%
		0.01	0.5	0.469	0.054	0.481	2.6%
			0.8	0.691	0.060	0.686	-0.7%
		0.05	0.5	0.150	0.036	0.159	5.4%
			0.8	0.220	0.035	0.234	6.1%
Opp' Path	0.8	0.005	0.5	0.541	0.048	0.533	-1.6%
			0.8	0.760	0.037	0.759	-0.2%
		0.01	0.5	0.424	0.041	0.447	5.1%
			0.8	0.655	0.046	0.658	0.5%
		0.05	0.5	0.171	0.047	0.158	-8.3%
			0.8	0.261	0.045	0.252	-3.8%
	0.9	0.005	0.5	0.598	0.053	0.585	-2.1%
			0.8	0.830	0.043	0.819	-1.4%
		0.01	0.5	0.474	0.050	0.494	4.1%
			0.8	0.705	0.043	0.720	2.0%
		0.05	0.5	0.187	0.051	0.177	-5.4%
			0.8	0.290	0.052	0.283	-2.6%

The comparison between the mean of the mission success probabilities derived from the simulations and the analytical solutions show that there are not significant

differences. As seen in the *Difference* column in Table 4, the differences do not exceed 8.3% of the Analytical Calculations. The differences come from two reasons. The analytical tool assumed the probability of encountering valid targets to be Poission distribution. However, a uniform distribution was adopted to represent the target distribution in the simulation model. Further, a limited number of simulation repetitions were run for each case. If we run the simulation model for greater number of runs, we can expect the difference will decrease. Despite the differences between the two values, these results suggest our simulation model is a reliable tool for predicting autonomous munition performance in simple battlefield scenarios.

4.2.2 Cooperative Behavior Investigation

With the exception of cooperative behavior, the mission parameters for the second step of the validity investigation simulation model are the same as those for the first step using the simulation model. The simulation results and analysis of the simulation data are presented in Table 5 and Table 7.

The analysis of the simulation result shows that the probabilities of valid target kill are usually increased by the adoption of the cooperative classification and engagement scheme. When the false target attack rates are low, the improvement is not significant, and in the case of two munitions executing the same path search, the low FTAR resulted in a decrease in performance for the cooperative munitions. However, as the false target attack rate increases, the probabilities of valid target kills are significantly improved proportional to the increase in the false target attack rates.

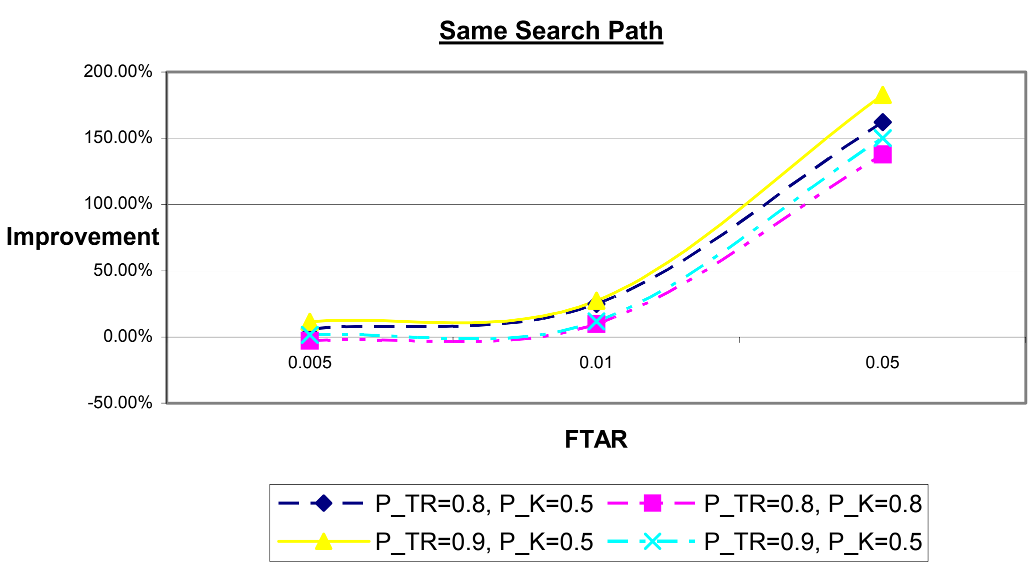
Table 5 Valid Target Kill Probability (Two munitions/Single target)

Parameters				No-Cooperation		Classify/Engage Cooperation		Improvement
Search PTN	P_{TR}	FTAR	P_K	Mean	Std Dev	Mean	Std Dev	
Same Path	0.8	0.005	0.5	0.516	0.061	0.547	0.046	6.01%
			0.8	0.723	0.045	0.703	0.048	-2.77%
		0.01	0.5	0.419	0.050	0.523	0.041	24.82%
			0.8	0.613	0.043	0.674	0.043	9.95%
		0.05	0.5	0.143	0.032	0.375	0.044	162.24%
			0.8	0.204	0.027	0.485	0.050	137.75%
	0.9	0.005	0.5	0.572	0.064	0.637	0.049	11.36%
			0.8	0.793	0.048	0.806	0.040	1.64%
		0.01	0.5	0.469	0.054	0.598	0.053	27.51%
			0.8	0.691	0.060	0.772	0.071	11.72%
		0.05	0.5	0.150	0.036	0.424	0.041	182.67%
			0.8	0.220	0.035	0.550	0.047	150.00%
Opp' Path	0.8	0.005	0.5	0.541	0.048	0.646	0.050	19.41%
			0.8	0.760	0.037	0.823	0.040	8.29%
		0.01	0.5	0.424	0.041	0.600	0.040	41.51%
			0.8	0.655	0.046	0.764	0.036	16.64%
		0.05	0.5	0.171	0.047	0.467	0.050	173.10%
			0.8	0.261	0.045	0.597	0.056	128.74%
	0.9	0.005	0.5	0.598	0.053	0.693	0.041	15.89%
			0.8	0.830	0.043	0.894	0.024	7.71%
		0.01	0.5	0.474	0.050	0.680	0.040	43.46%
			0.8	0.705	0.043	0.857	0.031	21.56%
		0.05	0.5	0.187	0.051	0.524	0.065	180.21%
			0.8	0.290	0.052	0.678	0.055	133.79%

Gillen[3] presented a different conclusion that “the cooperative behavior does not offer any advantage as the precision of the ATR is degraded and/or the clutter density increases which means higher FTAR.” However, Gillen considered cooperative attack only; there was no provision for multi-look cooperative classification in his work. He considered different mission parameters for the study of cooperative behavior effectiveness such as Time of Flight, Target Priority, Range Rate, and Number of

Munitions. Each of the parameters affected the second munitions decision to engage the target. When a munition classifies a target as valid one, another munition is supposed to confirm the classification for cooperation in the present study. However, the munitions were not able to execute cooperative classification in Gillen's simulation model. As we see, different cooperative behavior schemes present different conclusions as to their effectiveness. The difference between Gillen's results and those presented in Table 5 are attributed to the significantly reduced effective FTAR when cooperative classification is employed.

The lethality parameter, P_K, has a direct effect in that cooperative behavior is always more beneficial to the less lethal munition cases. This is not surprising since the lower lethality increases the need for multiple attacks on a single target. P_{TR} also affects the result of the mission success probabilities, but significantly less than FTAR and P_K. This result is in consistent with findings by Gillen using a different form of the cooperative behavior decision rule.



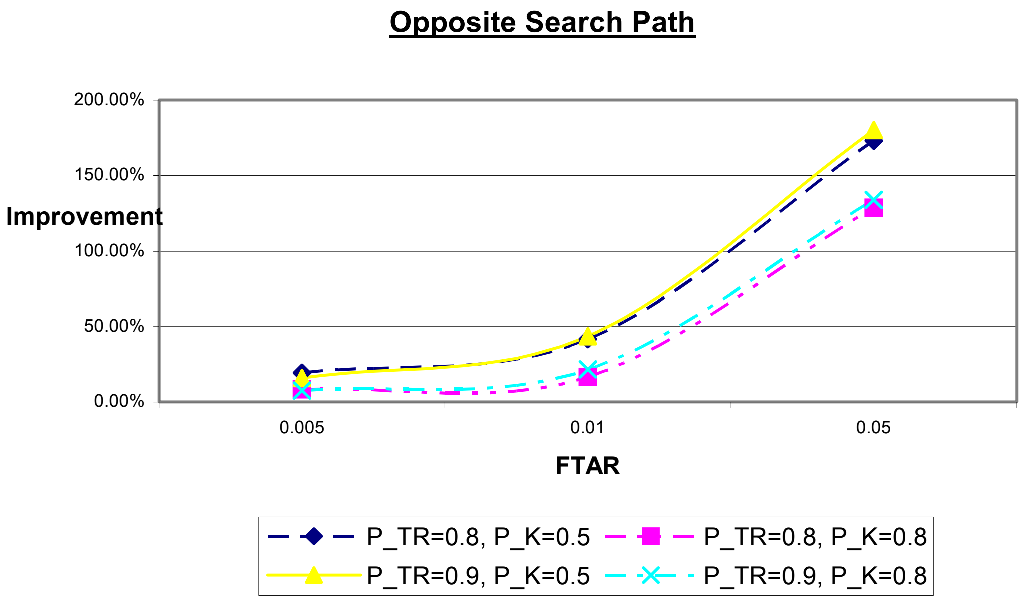


Figure 7 Improvement of Mission Success Probability

When we consider the search path based on the analysis of the mission success probabilities, we find in Table 6 that the opposite search path provides better results for valid target kills than the same path approach. Table 6 presents the improvement of the valid target kill probabilities based on each search patterns.

When non-cooperative behavior of the munitions was adopted, the improvement is very sensitive to change in FTAR. However, when cooperative behavior was adopted, the improvements don't vary nearly as much with FTAR as they did for the non-cooperative case. This result suggests that if multiple munitions are to be deployed, complementary search patterns are preferable to duplicative patterns. The complementary search patterns increase the chance that at least one of the munitions will encounter the target prior to a false target attack. This result is reinforced further when cooperative behavior is to be adopted for the classification and engagement scheme.

Table 6 Improved P_{MS} by the Opposite Search Path relative to Same Search Path (Two munitions/Single Target)

Mission Parameters			No-cooperation	Cooperation
P_{TR}	FTAR	P_K		
0.8	0.005	0.5	4.62%	15.33%
		0.8	4.87%	14.58%
	0.01	0.5	1.18%	12.83%
		0.8	6.41%	11.78%
	0.05	0.5	16.37%	19.70%
		0.8	21.84%	18.76%
0.9	0.005	0.5	4.35%	8.08%
		0.8	4.46%	9.84%
	0.01	0.5	1.05%	12.06%
		0.8	1.99%	9.92%
	0.05	0.5	19.79%	19.08%
		0.8	24.14%	18.88%

In addition to the analysis of the probabilities of valid target kills, it is important to analyze the result of the false target attacks. False target attacks waste munitions without any benefits. For the previous conditions, the predicted number of false target attacks is presented in Table 7.

It shows that the expected number of false target attacks decrease when cooperative classification is adopted because the total probability of false target attack given false target encounter is decreased with the multiplication of the number of multiple looks. This result suggests that cooperative classification can be used to reduce the number of required munitions for some scenarios due to a reduction in the expected number of "wasted" munitions, and it also means that the same amount of munitions with cooperative classification and attack scheme can provide improved capability in diverse engagement scenarios.

Table 7 Number of False Target Attacks (Two munitions/Single Target)

Parameters			No-Cooperation		Classify/Engage Cooperation		Improvement
Search PTN	P_{TR}	FTAR	Mean	Std Dev	Mean	Std Dev	
Same Path	0.8	0.005	0.524	0.070	0.099	0.041	-81.11%
		0.01	0.870	0.070	0.226	0.063	-74.02%
		0.05	1.688	0.043	0.804	0.085	-52.37%
	0.9	0.005	0.470	0.062	0.089	0.037	-81.06%
		0.01	0.806	0.066	0.191	0.071	-76.30%
		0.05	1.655	0.045	0.769	0.074	-53.53%
Opp' Path	0.8	0.005	0.498	0.050	0.083	0.039	-83.33%
		0.01	0.860	0.058	0.174	0.040	-79.77%
		0.05	1.674	0.052	0.646	0.106	-61.41%
	0.9	0.005	0.467	0.059	0.077	0.022	-83.51%
		0.01	0.812	0.070	0.157	0.044	-80.67%
		0.05	1.640	0.057	0.549	0.099	-66.52%

To investigate influence of the target numbers on the effectiveness of cooperative behavior, the simulation model was modified to include two valid targets. Table 8 presents the average number of valid target kills when two valid targets are uniformly distributed in the search area with other mission parameters being fixed. The effectiveness of cooperative behavior shows greater improvement over the non-cooperative cases for scenarios with lower P_K and higher FTAR. In some cases, cooperative behavior decreases the expected number of the valid target kills; specifically for scenarios with lower P_{TR} and higher P_K. The explanation for this is the further effective decreases in P_{TR} when cooperative behavior is adopted. The probability of target report decreases to P_{TR}^N based on the number(N) of multi-looks. However, since the increase of P_K and P_E[q] can compensate for the decrease in P_{TR}, the mission success

[q] Probability of Encountering Valid Targets

probability increases when cooperative behavior is adopted for lower P_{TR} and higher FTAR scenarios.

Table 8 Number of Valid Target Kills (Two munitions/Two targets)

Parameters				No-Cooperation		Classify/Engage Cooperation		Improvement
Search PTN	P_{TR}	FTAR	P_K	Mean	Std Dev	Mean	Std Dev	
Same Path	0.8	0.005	0.5	0.659	0.045	0.687	0.046	4.25%
			0.8	0.944	0.049	0.875	0.024	-7.31%
		0.01	0.5	0.573	0.050	0.647	0.055	12.91%
			0.8	0.831	0.051	0.838	0.031	0.84%
		0.05	0.5	0.248	0.036	0.496	0.048	100.00%
			0.8	0.361	0.046	0.636	0.036	76.18%
	0.9	0.005	0.5	0.680	0.046	0.703	0.041	3.38%
			0.8	0.938	0.040	0.916	0.029	-2.35%
		0.01	0.5	0.595	0.061	0.664	0.042	11.60%
			0.8	0.836	0.056	0.869	0.035	3.95%
		0.05	0.5	0.274	0.043	0.539	0.046	96.72%
			0.8	0.388	0.045	0.688	0.041	77.32%
Opp' Path	0.8	0.005	0.5	0.739	0.069	0.722	0.036	-2.30%
			0.8	1.162	0.072	0.917	0.025	-21.08%
		0.05	0.8	0.440	0.047	0.725	0.044	64.77%
	0.9	0.005	0.5	0.777	0.072	0.744	0.034	-4.25%
			0.8	1.240	0.052	0.940	0.021	-24.19%
		0.01	0.5	0.674	0.080	0.727	0.040	7.86%
			0.8	1.082	0.092	0.911	0.026	-15.80%
		0.05	0.5	0.287	0.044	0.609	0.052	112.20%
			0.8	0.462	0.044	0.784	0.045	69.70%

Table 9 presents the average number of the false target attacks when two target scenarios are examined with other mission parameters being fixed. The decrease in false target attacks is apparent across the board when cooperative behavior is employed. The analysis of Table 8 and Table 9 shows that a specific objective formula is necessary based on the desired performance since cooperative behavior may degrade the

performance of the autonomous weapon system in some battlefield scenarios. The objective formula should include the benefit of valid target kills and the loss due to false target attacks. This is because the cooperative behavior can decrease the number of valid target kills, and also decreases the number of false target attacks. The objective formula strategy will be discussed in the analysis of the next section.

Table 9 Number of False Target Attacks (Two munitions/Two Targets)

Parameters			No-Cooperation		Classify/Engage Cooperation		Improvement
Search PTN	P_{TR}	FTAR	Mean	Std Dev	Mean	Std Dev	
Same Path	0.8	0.005	0.397	0.054	0.069	0.034	-82.62%
		0.01	0.632	0.075	0.154	0.054	-75.63%
		0.05	1.477	0.068	0.619	0.065	-58.09%
	0.9	0.005	0.330	0.054	0.063	0.040	-80.91%
		0.01	0.556	0.091	0.152	0.050	-72.66%
		0.05	1.385	0.079	0.550	0.077	-60.29%
Opp' Path	0.8	0.005	0.384	0.049	0.055	0.037	-85.68%
		0.05	1.451	0.051	0.469	0.098	-67.68%
	0.9	0.005	0.342	0.042	0.038	0.027	-88.89%
		0.01	0.579	0.082	0.105	0.046	-81.87%
		0.05	1.412	0.049	0.365	0.093	-74.15%

4.3 Cooperative Behavior Investigation Model

The data presented in this section came from the AFRL/VACA simulation model. Previously, Dunkel[9] studied the effectiveness of cooperative behavior in autonomous wide area search munitions using the simulation model. Generally, the cooperative behavior is believed to improve the performance of the autonomous weapon system. However, Dunkel concluded that cooperative behavior does not always promise performance improvement for autonomous munitions. He found the effectiveness of

cooperative behavior depends on the cooperative scheme and battlefield scenarios. This conclusion is consistent with the analysis of the Validity Investigation Model discussed in section 4.2. Though it may not represent the real world autonomous munitions, the VACA simulation model is expected to give better insight on the performance of the autonomous munitions. This research provided an expansion of Dunkel's study of the cooperative behavior effectiveness. Dunkel explored three types of cooperative schemes; No Cooperation, Cooperative Engage, and Cooperative Engage & Classification. However, this research investigated only two of those cooperative behaviors; No Cooperation and Cooperative Engage & Classification. In addition to the analysis of cooperative behavior effectiveness, this research will focus on examining the efficiency of each munition by comparing the results of simulations with four and eight munition scenarios. Four targets, two of each type, are uniformly distributed in 100 square miles of search area, and those targets have no priority values based on the target type. The range of other input parameters for the Cooperative Behavior Investigation Model is given in Table 10.

Table 10 Simulation Parameters Allocation (Cooperative Behavior Investigation Model)

Parameters	Conditions	Range
Number of munitions	Investigate the efficiency of each munition	4, 8
False target density	Varies based on the number of false targets	0.05, 0.1
P_{TR}	Represent the ATR capability	0.95, 0.8
$P_{FTA\|E}$	Represent the ATR capability	0.1, 0.2
P_K	Represent the lethality of warhead	0.5, 0.8
Weighting factor	Calculate the task benefits	0.1~0.5

Except for the number of munitions, mission parameters given in Table 10 are environmental factors and system parameters. Though it may not provide sufficient validity for the statistical analysis, thirty runs were executed in each scenario. The analysis of the simulation results is discussed in the following two sections.

4.3.1 Analysis of Cooperative Behavior Effectiveness

For the first step, the effectiveness of cooperative behavior is investigated based on the number of valid targets killed and the number of false target attacks. The Validity Investigation Model discussed in section 4.2.2 demonstrated that cooperative classification and attack increased the expected number of valid targets killed and decreased the number of false target attacks, especially in high false target attack rate cases. However, the Validity Investigation Model cannot represent a real world autonomous weapon system; some impractical assumptions, such as no time delay and no resource consumption for additional classification process, are made for the purpose of simplicity. The Cooperative Behavior Investigation Model also may not represent the real world weapon system. However, the expanded consideration of diverse mission parameters describing the operational factors more precisely models the influence of each mission parameter on the munitions performance. Table 11 shows the cooperative behavior effectiveness of 4 munitions and 4 valid targets scenarios. The column *Number of Kills* represents the average number of valid targets killed and *Number of FTA* means the average number of false target attacks.

The result of Cooperative Behavior Investigation Model does not meet with the expectations and the conclusion of Validity Investigation Model. It is believed that the cooperative behavior will improve the performance of autonomous munitions, and the

analysis of Validity Investigation Model showed that the cooperative classification and attack scheme increases the expected number of targets killed in lower P_K and higher FTAR scenarios. However, the cooperative classification and attack scheme in the Cooperative Behavior Investigation Model decreases the expected number of valid targets killed ranging from 18% to 71% in all engagement scenarios. One of the reasons for the difference between two results might be that the Cooperative Behavior Investigation Model accounts for loss of search time due to confirming classifications. When a munition is called to reclassify a previously encountered object, it moves to the reported area with no time delay in the Validity Investigation Model. However, moving time to the reported area is considered in the Cooperative Behavior Investigation Model. The trend that the cooperative behavior will decrease the number of valid target kills will get even worse for non stationary targets.

Table 11 Number of Targets Killed / False Target Attacks (4 Munitions / 4 Targets)

			No-Cooperation		Classify/Engage Cooperation		Number of Kills Improvement	False Target Attack Decrease
P_{TR}	P_K	FTAR	Number of Kills	Number of FTA[r]	Number of Kills	Number of FTA		
0.8	0.5	0.005	1.267	0.600	1.033	0	-18.47%	-100%
		0.01	0.828	0.730	0.400	0	-51.69%	-100%
		0.02	0.800	1.567	*	*	*	*
	0.8	0.005	1.733	0.600	*	*	*	*
		0.01	1.500	1.033	0.433	0	-71.13%	-100%
		0.02	1.300	1.567	0.467	0	-64.08%	-100%
0.95	0.5	0.005	1.367	0.567	0.600	0	-56.11%	-100%
		0.01	1.100	0.867	0.677	0.032	-38.45%	-96.31%
		0.02	0.805	0.961	0.633	0	-21.37%	-100%
	0.8	0.005	1.867	0.567	*	*	*	*
		0.01	0.935	0.759	0.667	0.033	-28.66%	-95.65%
		0.02	1.500	1.500	0.667	0	-55.53%	-100%

[r] False Target Attacks

When we look into the number of false target attacks, we note a dramatic decrease in the expected number. The decrease of both the number of valid targets killed and the number of false target attacks means that more munitions end up running out of gas without attacking anything. If the munitions are in a battlefield with higher valid target density, the waste of munitions resulted from running out of gas will be decreased and the effectiveness of cooperative behavior is expected to improve.

Table 12 Number of Targets Killed / False Target Attacks (8 Munitions / 4 Targets)

			No-Cooperation		Classify/Engage Cooperation		Number of Kills Improvement	False Target Attack Decrease
P_{TR}	P_K	FTAR	Number of Kills	Number of FTA	Number of Kills	Number of FTA		
0.8	0.5	0.005	1.500	1.100	1.300	0.067	-13.33%	-94%
		0.01	1.667	2.367	1.567	0.167	-6.00%	-93%
		0.02	1.500	3.733	1.400	0.233	-6.67%	-94%
	0.8	0.005	2.500	1.100	1.767	0.067	-29.32%	-94%
		0.01	2.333	2.267	1.600	0.033	-31.42%	-99%
		0.02	1.933	3.567	1.733	0.433	-10.35%	-88%
0.95	0.5	0.005	1.833	1.033	1.833	0.067	0.00%	-94%
		0.01	1.800	1.867	1.700	0.133	-5.56%	-92.88%
		0.02	1.567	3.233	1.900	0.267	21.25%	-92%
	0.8	0.005	2.900	1.033	2.333	0.033	-19.55%	-96.81%
		0.01	2.833	1.867	2.300	0	-18.81%	-100.00%
		0.02	2.333	3.167	2.100	0.233	-9.99%	-93%

Table 12 shows the cooperative behavior effectiveness in 8 munition scenarios with the other mission parameters being fixed. Except for the less decreased rate of valid targets killed, the effectiveness of cooperative behavior in 8 munition scenarios is similar to that of 4 munition cases. The difference we can find between Table 11 and Table 12 is that cooperative classification and attack scheme does not decrease the number of targets killed as many as 4 munitions cases. However, it still prevents most false target attacks.

This suggests that cooperative behavior in autonomous munitions offers greater benefits when there are greater number of munitions, i.e. swarms.

4.3.2 Effectiveness of the Number of Munitions

Table 13 shows that cooperative behavior provides higher efficiency of each munition when greater number of autonomous munitions are deployed in a battlefield area as depicted above.

Table 13 Efficiency of Each Autonomous Munition

			No-Cooperation			Classify/Engage Cooperation		
P_{TR}	P_K	FTAR	4 munitions	8 munitions	Efficiency Improve	4 munitions	8 munitions	Efficiency Improve
0.8	0.5	0.005	0.317	0.188	-40.81%	0.258	0.163	-37.08%
		0.01	0.207	0.208	0.66%	0.100	0.196	95.88%
		0.02	0.200	0.188	-6.25%	*	0.175	*
	0.8	0.005	0.433	0.313	-27.87%	*	0.221	*
		0.01	0.375	0.292	-22.23%	0.108	0.200	84.76%
		0.02	0.325	0.242	-25.65%	0.117	0.217	85.55%
0.95	0.5	0.005	0.342	0.229	-32.96%	0.150	0.229	52.75%
		0.01	0.275	0.225	-18.18%	0.169	0.213	25.55%
		0.02	0.201	0.196	-2.67%	0.158	0.238	50.08%
	0.8	0.005	0.467	0.363	-22.34%	*	0.279	*
		0.01	0.234	0.354	51.50%	0.167	0.288	72.41%
		0.02	0.375	0.292	-22.23%	0.167	0.263	57.42%

The values in columns of *4 munitions* and *8 munitions* represent the expected number of valid targets killed by one munition. Mostly, when no cooperation was executed, the efficiency of each munition degraded by increasing the number of autonomous munitions from 4 to 8. However, when cooperative classification and engagement was adopted, the efficiency of each munition rose with the increased number of autonomous munitions. This does not mean that more munitions will always produce higher efficiency since the

increased number of munitions also yields a higher rate of wasted munitions that run out of gas. However, the result shows that sufficient amount of autonomous munitions are required to maximize the efficiency of each autonomous munition.

Number of targets killed and false target attacks are only two of many metrics that can be used to evaluate weapon system performance. In the real world battlefield, there can be many diverse ways of measuring the performance of a weapon system. Different types of targets can have different profits, and the losses from false target attacks can vary based on rules of engagement and specific operational objectives. This means that a specific objective function which reflects the operational objectives and engagement environment is required for measuring the performance of a weapon system. The analysis of the objective function will provide better insight for optimal operational parameters based on the environmental factors and system parameters.

V Conclusions and Recommendations

5.1 Conclusions

This research presented validity investigation of a simulation model as a performance measurement tool, and effectiveness investigation of cooperative behavior in autonomous wide area search munitions. Though conceptual simplification and limited ranges of operational parameters were adopted, the two simulation models presented useful information for the effectiveness of cooperative behaviors and the function of each mission parameter.

There are common features in the conclusions with respect to both simulation models. However, it will be discussed in two parts based on each simulation model since there are also unique factors in each consequence.

5.1.1 Validity Investigation Model

The first simulation model, defined as the Validity Investigation Model, is not applicable to represent practical operation of the autonomous weapon system. However, it is useful for examining how each of the mission parameters affects the performance of autonomous munitions. The validity investigation process, presented in Section 4.2.1, demonstrated that a simple valid simulation model is able to provide significant trends for a real world weapon system. Through the cooperative behavior investigation, discussed in Section 4.2.2 using the result of the same simulation model, the performance of a cooperative behavior scheme and the effects of mission parameters were examined. Though it is not real, the analysis of the simulation result derived from the Validity Investigation Model offered clear understanding on the effects of mission parameters. In

cases of lower P_{TR}, lower FTAR with higher P_K, the cooperative classification and attack scheme did not increase the number of valid target kills. This suggests that the cooperative classification and attack scheme should not be adopted under these conditions. However, even though cooperative behavior may degrade the performance for killing targets, the decreased number of false target attacks can provide improved performance of autonomous weapon system.

Cooperative behavior may or may not improve the performance of autonomous munitions since the chosen objective function significantly affects the performance of the autonomous weapon system. The effect of each mission parameter also varies with the objective function. However, this does not mean that it is impossible to predict how the system parameters influence the performance of autonomous search munitions. For example, if an accurate ATR system can be employed, the cooperative classification will not degrade the performance of autonomous weapon system.

5.1.2 Cooperative Behavior Investigation Model

The Cooperative Behavior Investigation Model included additional mission parameters to establish a more accurate simulation model of real world autonomous search and attack weapon system. However, it still requires simplifying assumptions and has its limitations. Though this VACA simulation model still can not represent a real world autonomous weapon system accurately, the extended consideration of mission parameters offered better prediction of the autonomous munitions performance. As discussed in the previous section, cooperative behavior reduced the number of valid targets killed and false target attacks. This means that more autonomous munitions end

up running out of gas. If the life of the autonomous munitions were extended, more munitions might find and attack additional valid targets.

When the influence of munition numbers was examined, increased amount of munitions deployed demonstrated more efficient employment of the autonomous munitions. When the cooperative classification and attack scheme was adopted, the probability that any given munition will kill a valid target rose when the number of deployed munitions was increased. This suggests that cooperative behavior might best be employed under higher target density scenarios with larger number of munitions. However, the increased number of autonomous munitions does not always provide better performance of the overall system. Additional munitions exceeding optimal amount will diminish the average efficiency of the autonomous munitions.

Both the Validity Investigation Model and Cooperative Investigation Model demonstrate that cooperative behavior does not guarantee improved performance of autonomous munitions. The effectiveness of cooperative behavior depends on environmental factors, system parameters and the objective function. To find the optimal operational parameters, such as number of munitions, search patterns, cooperative behavior scheme, those three factors should be determined clearly before examining the effects of each operational parameter.

5.2 Recommendations for Further Research

There is no clear definition representing optimal performance of autonomous weapon system since the objective of a specific operation varies by the engagement environment and operational directives. As the starting point of performance investigation, it is recommended that an objective function should be established which

defines the performance of autonomous weapon system. The function can consider only the number of targets killed like this research adopted. However, extended consideration of mission result, such as the number of false target attacks and the number of munitions that ends up running out of gas, will present better information for the performance analysis. If various types of valid targets are employed, different target priority can score different benefit values to each target type.

To simplify simulation models, many assumptions were made. Though the simulation model could not precisely represent the real world weapon system, limited information acquired from the simulation model can help to improve the weapon system. Successive elimination of the assumptions and limitations is required for continued research.

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14. ABSTRACT

The purpose of this study is to investigate how a simulation model can accurately represent the performance of the autonomous wide area search munitions, and to find the effectiveness of the cooperative behavior on the autonomous munitions. As a prediction tool for measuring the performance of the virtual weapon systems, simulation models are established because there are insufficient analytical tools for the prediction of weapon system performance. For the first phase, this thesis presents how accurately a simplified simulation model can represent a proposed weapon system by comparing the simulation results to the analytical solutions. For the second phase, this research investigates how each mission parameters including cooperative behavior affects the performance of the weapon system. Though it does not provide a practical solution for the development of the autonomous wide area search munitions, this research will show some meaningful allocations of the munitions tasks that are applicable to the development of the autonomous munitions.

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